THE ROLE OF GROUND TRUTH IN IMPROVED IDENTIFICATION OF MINING EXPLOSION SIGNALS
UTILIZATION OF CALIBRATION EXPLOSIONS AND ACOUSTIC SIGNALS

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ABSTRACT

The characterization and identification of small magnitude seismic sources using regional observations involves the analysis of signals from natural and man made sources. Proper event classification will depend upon the appropriate assessment of source and propagation path effects. Our work is intended to investigate supplementary procedures and data sets that can improve source characterization procedures. Several approaches to improved source identification procedures have been investigated including: (1) Execution of contained calibration explosions; (2) Utilization of regional array data for improved separation of source and propagation path effects; (3) Development of in-mine ground truth through mine records or on site instrumentation; (4) Combining seismic and infrasound data for source characterization.

A series of single-fired calibration shots were detonated in a mine in NE Wyoming for the purpose of developing source scaling relations and comparison to typical delay-fired explosions. Regional data from these explosions are consistent with a simple Mueller-Murphy source model.

The variation in seismograms across regional arrays is used to contrast local site effects with source and regional propagation contributions. The three IMS arrays in the western US - TXAR, PDAR and NVAR- were used in the study. TXAR with its homogeneous geology shows the least variability and NVAR with instruments in seven different rock types shows the greatest variation in both amplitudes and wave shapes.

Ground truth from controlled mining explosions can be obtained from typical blasting records maintained by the mines or more directly from close-in seismic and acoustic observations from within the mine. Mines in the Iron Range (IR) of Minnesota, the Powder River Basin (PRB) in Wyoming, and the Porphyry Copper District (PCD) of east central Arizona and south west New Mexico were used in gathering ground truth ranging from mine records (IR) to in-mine monitoring (PRB and PCD). The contribution of this information to regional monitoring is compared and contrasted.

The focus of this paper will be on the in-mine ground truth developed in the PCD and applied to to regional seismic and infrasonic signals. Seismic and infrasonic signals both in-mine and at regional distances will be used in characterizing the source and propagation path effects.

Key Words: ground truth, mining explosion, seismo-acoustic, infrasound, regional, and calibration

OBJECTIVE

Regional arrays designed for monitoring purposes will detect both natural and man made sources. Many of the artificial sources can be associated with mining operations (Heuze and Stump, 2000). It is important that these sources be properly characterized and found distinct from a nuclear explosion. This discrimination process has historically depended upon seismic data. Recent work (Sorrells *et al.*, 1997; Hsu and Stump, 1997; Hagerty *et al.*, 1999; Sorrells *et. al*, 2000; Stump *et al.*, 2000) has suggested that the association of infrasonic signals with seismic might be useful in the characterization of a source as a near-surface mining explosion with its accompanying infrasound signal.

The efficiency of infrasonic wave propagation is well known to be strongly affected by the direction and magnitude of atmospheric winds. Seasonal variations in detection thresholds for infrasonic waves associated with mining explosions have been documented (Sorrells *et al.*, 1997; Hsu and Stump, 1997). Average atmospheric models predict no infrasonic returns until a distance range of several hundred

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kilometers. Several researchers (Hagerty *et al*, 1999; Stump *et al.*, 2000; and Sorrells *et al*, 2000) have reported robust observations in the 50 - 250 km range indicating that seasonal winds may be important to these observations.

The work reported in this paper is motivated by a need to understand atmospheric effects on infrasonic propagation and the possibility of using infrasound and seismic waves to identify mining explosions. The approach we have taken is empirical in that the first step has been the design, construction and installation of monitoring equipment that can produce a comprehensive data set. A regional size network of seismic and infrasound sensors, some of which are arrays, has been designed using a combination of new and existing facilities (Figure 1).

Key to the success of this operation is the development of ground truth information pertinent to the mining sources. Based upon previous studies of large coal cast blasting operations in Wyoming that trigger the IMS (Hedlin *et al. 2000*), the porphyry copper region of Arizona and New Mexico was chosen for the study. Mining explosions for hard rock mining are primarily designed to fracture the material but not move the rock. This blasting practice is in strong contrast to coal cast blasting where the primary goal is to move the overburden into the pit.

This mining region is bounded by the two arrays, NVAR and TXAR, providing the link to the IMS. Critical to the success of the experiment has been cooperation with the local mines producing the sources. Close cooperation has been developed with the Phelps Dodge mines in Morenci, Arizona and Tyrone, New Mexico where in-mine seismic and acoustic systems have been deployed and are operated for ground truth. Additional cooperation is ongoing with the Black Mesa Coal Mine in NE Arizona providing data from large scale cast blasts. Additional cooperating organizations in this regional study include Los Alamos National Laboratory (Rod Whitaker, LANL and ST. GEORGE), University of Arizona (Terry Wallace, TUC and WUAZ) and University of Texas, El Paso (Diane Doser).

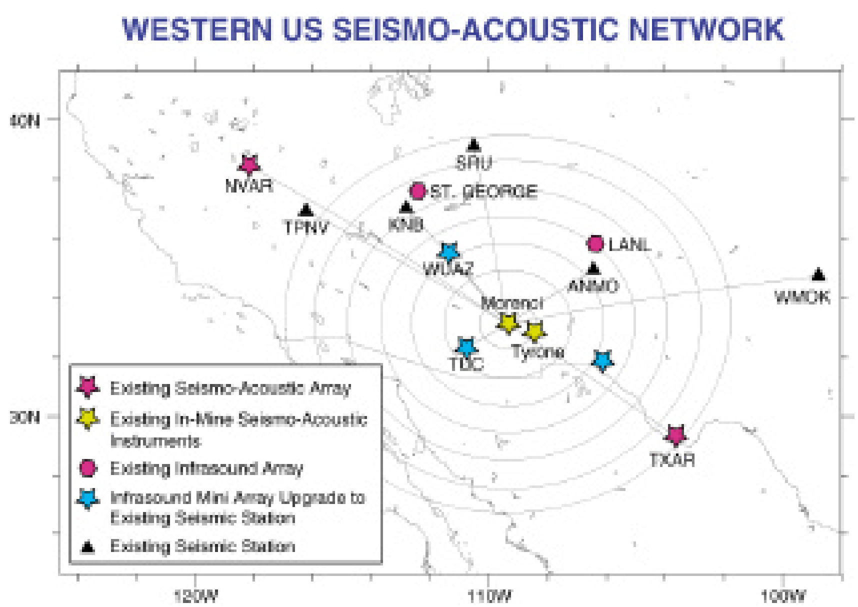

Figure 1: Map depicting the seismo-acoustic array that is being used to study the effect of mining practices and atmospheric models on the generation and propagation of seismic and infrasound signals.

The resources in this seismic and infrasonic network (Figure 1) will provide the opportunity to study seismo-acoustic signals (and seismic alone) from a large number of blasts in order to constrain both source and propagation path effects. In addition to this permanent array, a set of five portable seismo-acoustic

data acquisition systems have been constructed for the purposes of filling in the details of propagation path effects between the network stations.

Installation of the infrasound components to TUC and WUAZ are continuing in the summer of 2000 as well as the establishment of the seismo-acoustic site near El Paso, Texas. Parallel with this installation has been the construction of a ground truth data base from the majority of the resources in the network including the ground truth stations in the mines. We report on preliminary findings from this data set.

RESEARCH ACCOMPLISHMENTS

In-Mine Monitoring Systems for Ground Truth. The in-mine monitoring systems consist of a three-component broadband STS-2 (Figure 2) sensor and RefTek digitizing and archival system and small aperture acoustic array.

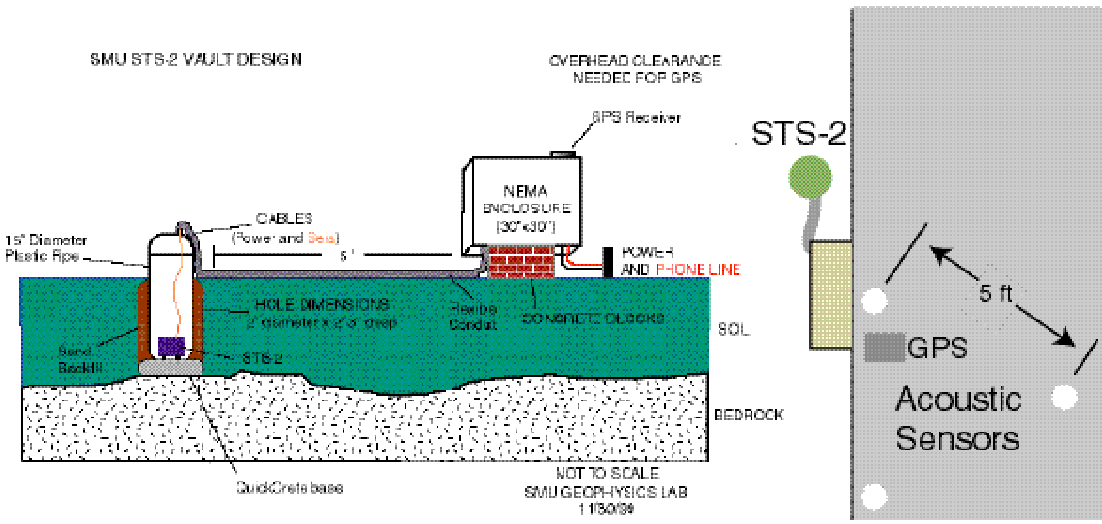

Figure 2. Schematic of the vault design and NEMA enclosure for in-mine deployments. The relative locations of the seismometer and acoustic gauges are shown to the right.

The recording devices for the system are housed in a 30" X 30" standard NEMA (Figure 3) enclosure. The RefTek 72A-08 digitizer is attached to a 4GB hard disk by a SCSI cable. Also, monitoring the data flowing into the hard drive is another computer-- the RefTek 114. This unit analyzes the data for triggered events and either dials out with event information or can be accessed for remote inquiry. Raw data from the hard drive can be transferred from the station to SMU where analysis for start time, shot size, and additional parameters occurs. Electrical power for each station is provided by a 12-volt car battery recharged by a trickle charger connected to 110 VAC. The total system amperage draw is 1.2 amps facilitating the use of commercial power as opposed to solar power. Accurate timing information at each station is obtained via GPS satellite clocks mounted to the top of the enclosure.

The instrument deployment in the Morenci Mine is illustrated in Figure 4 with similar equipment at Tyrone, NM. The site is centrally located in the main pit of the mine and provides coverage for the entire mine. The ore body at the Morenci mine is a large granite/granodiorite complex that has undergone hypogene alteration during the Laramide orogeny. The ore body is bounded on all sides by normal faulting. The current blasting method used at Morenci is designed to fragment the material and does not involve material casting. The 62' holes (that includes 50' for the bench and 12' subgrade) are drilled with a 12.25" or 13.75" drill bit. The drilling is conducted on a 24 hour operations schedule, while blasting is limited to daylight hours. An ANFO slurry is then loaded into the holes to a depth of 28-30'. Above the ANFO, the hole is stemmed with drill cuttings. The production at Morenci calls for approximately 300-400 holes per day with between 1500-2000 lbs/hole. The blasting engineers use 17-40 msec non-electric

surface delays between each hole firing, and approximately 80% of the shots are designed in a Chevron pattern with the remainder being fired en echelon.

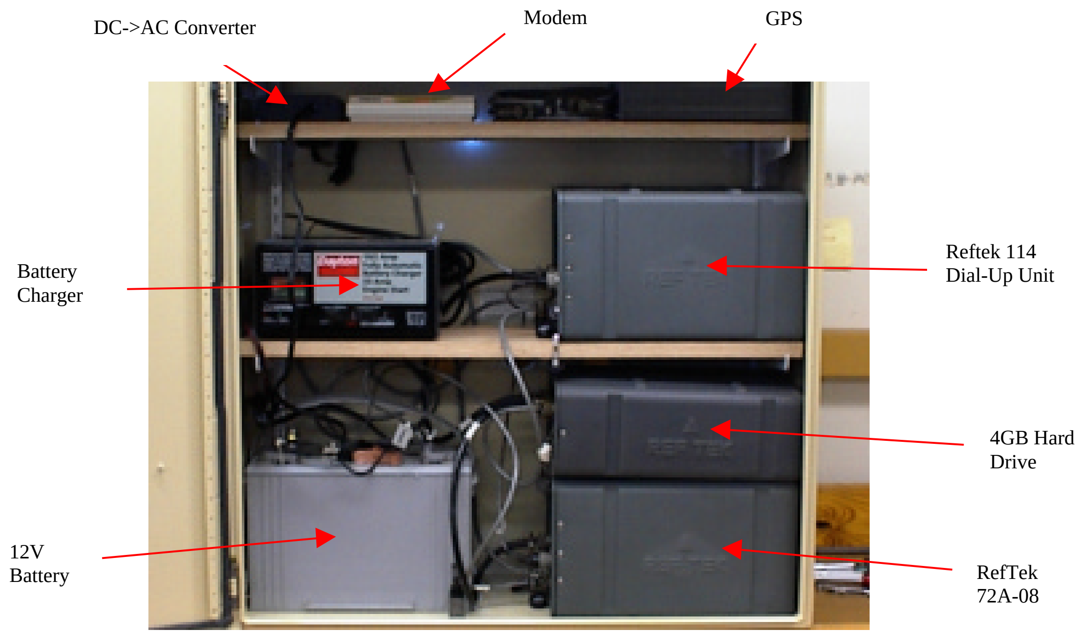

Figure 3. NEMA enclosure housing RefTek data acquisition equipment, including the RefTek 114 dial-up unit.

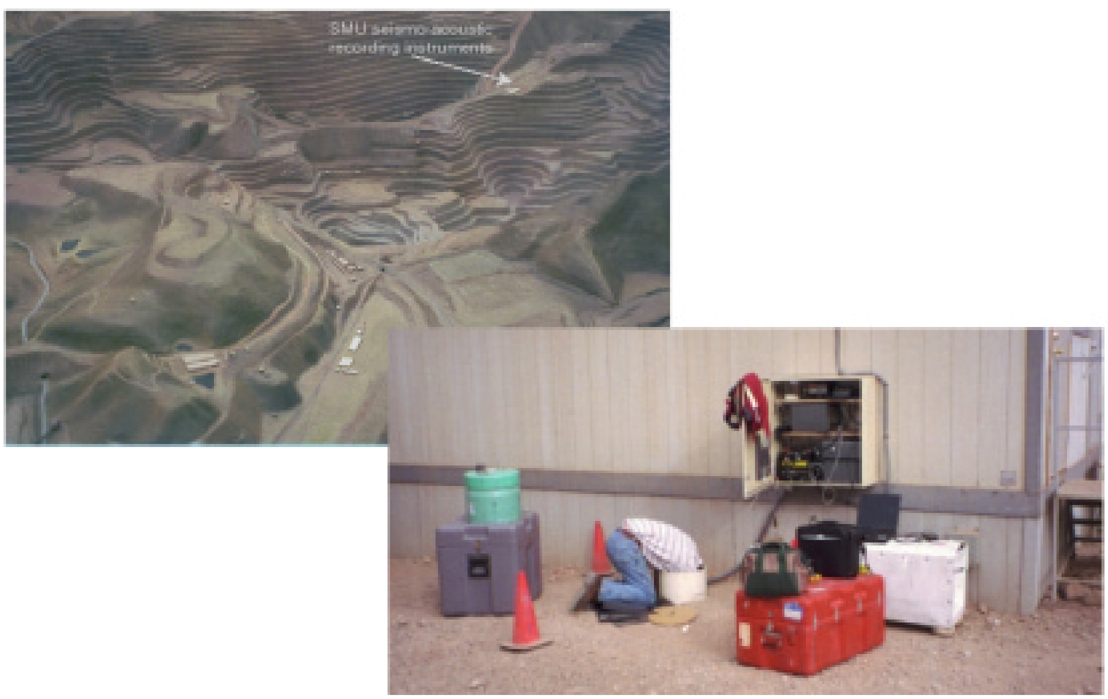

Figure 4: The pit location of the in-mine system at Morenci is illustrated in the upper left. The actual system during installation is pictured in the lower right.

Regional Seismic and Infrasonic Installations. The regional instrumentation that is being installed under this work is designed much like the in-mine system based upon Ref Tek data loggers and Ref Tek 114 where there is telephone service. The power system is solar at the remote sites. The infrasonic component consists of three, Chapparel Model 2 microphones modified to operate at 12 volts. The three sensors are arranged in a triangular pattern with 100 m separation. Eight, 25' porous hoses as illustrated in Figure 5, provide noise reduction.

Figure 5: One element of a regional infrasound array. The porous hoses are summed by the manifold shown in the lower right, which is connected to the Chapparel Model 2 microphone.

Seismo-Acoustic Network Results. The in-mine stations were deployed in January 2000 followed by the initial regional infrasound stations. A preliminary data base of ground truth events has been built and provides the basis for the analysis reported. An example event is reproduced in Figure 6 including the in-mine and regional data. This particular explosion is from Morenci and illustrates the types of regional signals that this blasting generates.

For purposes of this preliminary summary we have focused on a limited collection of events with ground truth from the mine. The events and their characteristics are summarized in Table 1. There are several interesting conclusions that can be drawn from this ground truth data set. Shot sizes ranged from 10,980 to 605,820 lbs, almost two orders of magnitude. It is also worth noting that it is often the case that multiple patterns or arrays of explosions may be simultaneously or nearly simultaneously detonated producing a complex interaction that may be seen at local and regional distances. The source duration, as quantified by the shot delay times, span a relative narrow range between 0.30 to 2.19 s. Two of the patterns (Events 6 and 8) were composed of shots that included no delay times. A wide-range of blasting practices is reflected in this tabulation providing an opportunity to quantify the effect of these source parameters on the seismic and infrasonic signals.

The in-mine acoustic signals that accompany the events listed in Table 1 are reproduced in Figure 7a. One can identify a range of amplitudes and wave shapes reflective of the variation in blasting practices. Event 1, which is also reproduced in Figure 6, consisted of the detonation of three distinct explosive patterns. This source characteristic is reflected in the complex pattern in the acoustic waveform. A filter panel for Event 1 (Figure 7b) further illustrates the complexity of the waveform produced by the detonation of the three patterns. The in-mine acoustic frequency content is quite broadband extending from several seconds to tens of Hertz.

Contrasting the acoustic signal from Event 1 with that from Event 3 (single pattern), illustrates that the single source produces a simple acoustic pulse that might be used to interpret the more complicated detonations. These results also suggest that the in-mine observations can be used in developing ground truth from the blasts and identifying multiple pattern shots. One can also imagine that a combination of

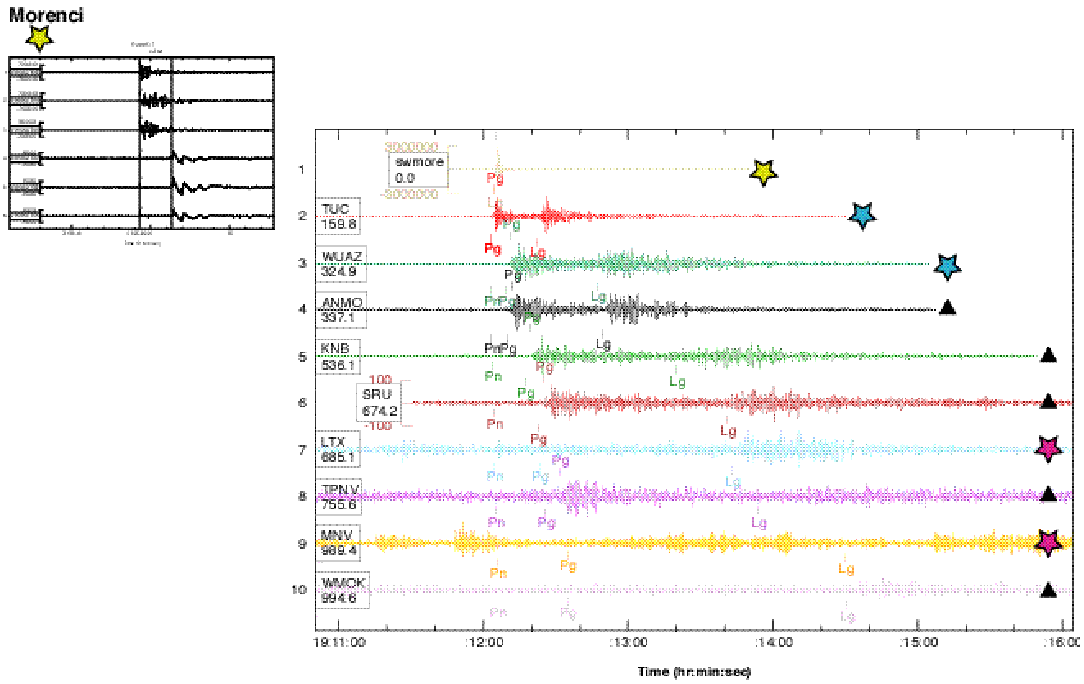

Figure 6: The in-mine seismic (first 3 waveforms) and acoustic data (second 3 waveforms) (upper left) and regional network data (seismic) (lower right) from a Morenci blast. The symbols to the right of each waveform correspond to the station types illustrated in Figure 1.

Table 1: Blast Parameters

Event #	Date	Number of Patterns	Total Charge in lbs.	Shot Duration (s)
1	3/13/00	3	184320 90850 50750	0.88 0.65 0.30
2	3/13/00	2	108620	0.43
3	3/10/00	1	31450	0.83
4	3/10/00	1		
5	3/10/00	1	102620	0.54
6	3/09/00	2	10980	0.00
7	3/08/00	1	385070	1.13
8	3/07/00	2	170870 18640	0.80 0.00
9	3/06/00	1	36110	0.95
10	3/03/00	3	141030	0.25
11	3/03/00	1	83100	1.29
12	3/02/00	1	55930	0.85
13	3/02/00	2	35170 125730	0.93 0.78
14	3/02/00	1	19070	0.69
15	3/01/00	2	241180 286330	0.84 0.85
16	2/25/00	1	605820	2.19
17				
18	2/24/00	3	32400 50790 23710	0.45 0.79 0.61

seismic and acoustic observations could be used for locating events within the mine. As Figure 4 illustrates, the mine is quite large with blasting in number of different areas.

The peak amplitude of the acoustic signal from the detonation of each pattern listed in Table 1 was plotted against the total amount of explosives (Figure 8a). The data indicates a strong correlation between peak amplitude in the acoustic signal and the total amount of explosives. There are three data points that fall outside this positive correlation which warrant further study.

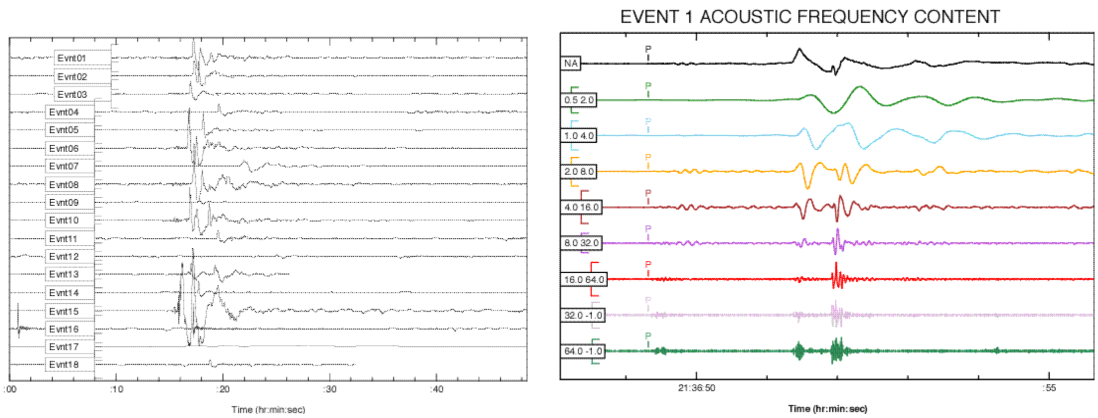

Figure 7: a-left) Acoustic signals from the in-mine instrumentation illustrated in Figure 4. The signals from the eighteen events for which ground truth information is listed in Table 1 are included. b-right)Bandpass filter panel for the in-mine acoustic data from Event 1.

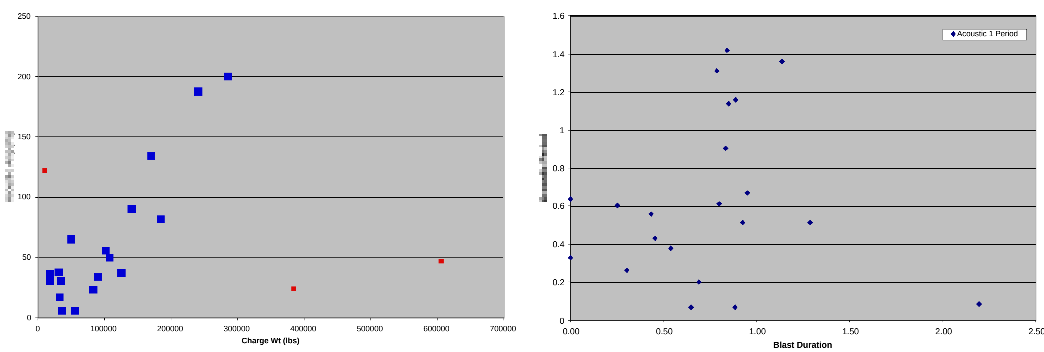

Figure 8: a-left) Peak acoustic amplitude from the in-mine data is plotted against the total explosive yield for the shots listed in Table 1. b-right) The pulse width of the acoustic signal is plotted against explosive source duration as defined by the shot delay times.

There is not as clear of a relationship between the period of the acoustic signal and the duration of the blast. Signal period does increase with source duration although it appears from the data in Figure 8b that there is more than just blast delay times that are contributing. Little is known about these individual shots other than information gathered from the blasting log.

A complementary analysis of the in-mine seismic data for the events in Table 1 was also undertaken. The vertical waveforms from the STS-2 for the same events is reproduced in Figure 9a. The STS-2 was installed in hopes of exploring the long period part of the signal at close ranges. Careful examination of the data suggests that clipping is experienced for the largest of the signals. A filter panel of the vertical waveform from Event 1 (unclipped) is reproduced in Figure 9b. This plot illustrates that the signals have significant long period energy, particularly for the shear arrivals. The compressive energy dominates the highest frequencies.

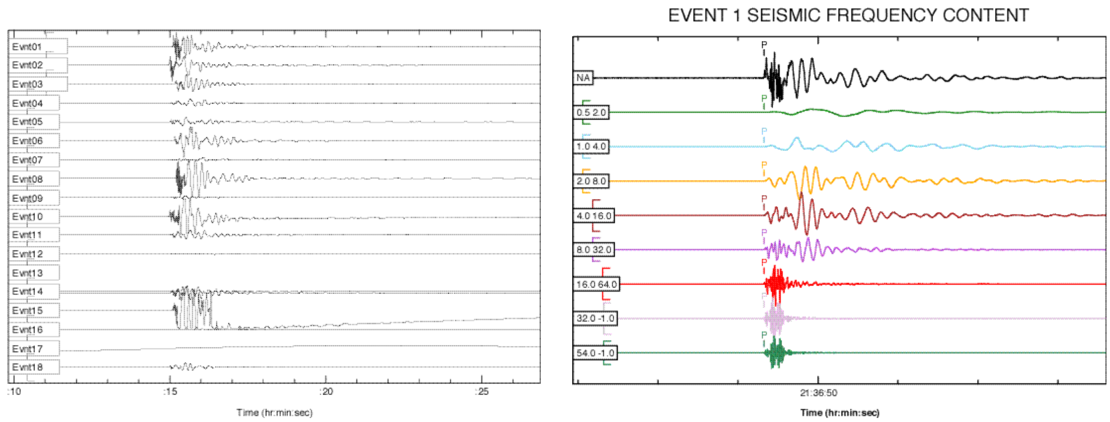

Figure 9: a-left) Vertical seismic signals from the in-mine instrumentation illustrated in Figure 4. The signals from the eighteen events for which ground truth information is listed in Table 1 are included. b-right)Bandpass filter panel for in-mine seismic data from Event 1.

Unlike the acoustic data, there appears to be little relationship between peak seismic amplitude and total amount of explosives. Typically the delay patterns developed for mining blasts are designed to maximize rock fragmentation and minimize ground motion within the mine and the surrounding area at frequencies above several Hertz. The peak amplitude data reproduced in Figure 10 supports this interpretation in contrast to the acoustic signal. It appears that the in-mine acoustic signals may better reflect the total size of the mining explosion whereas the seismic data may be constrained by the something like the maximum amount of explosives per borehole or per delay period. The in-mine data developed during this study will provide the opportunity to further explore these effects. No attempt has been made to correct for spatial decay at this preliminary stage which can also be an important effect for sources in a mine as big as that illustrated in Figure 4.

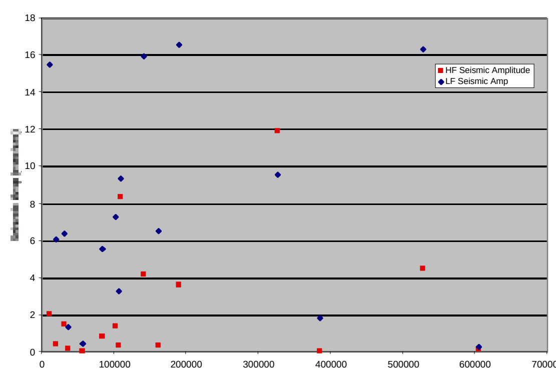

Figure 10: Peak amplitudes from the in-mine seismic data were measured in two bands, high frequency (HF - red symbol) at 20 Hz and wide band (LF - blue symbol) centered near 5 Hz.

The regional seismic data from one of the regional seismic stations (TUC) is summarized and compared to the ground truth information. Time domain peak amplitudes for the three regional phases, P_g, L_g and R_g were measured and plotted against total charge weight in Figure 11. The amplitudes for each phase vary by an approximate order of magnitude. Generally the L_g amplitudes are the largest. The data indicates a general increase in amplitude with total explosive yield.

Subsequent analysis of the complete network of regional data will provide a quantification of regional variations in amplitude and frequency content of the signals. Relating this to ground truth information such as that reproduced in Table 1 will provide the basis to assess important monitoring issues for small size

explosions. Although unanalyzed at this point, the explosions fired with no delays provide an important control in this analysis.

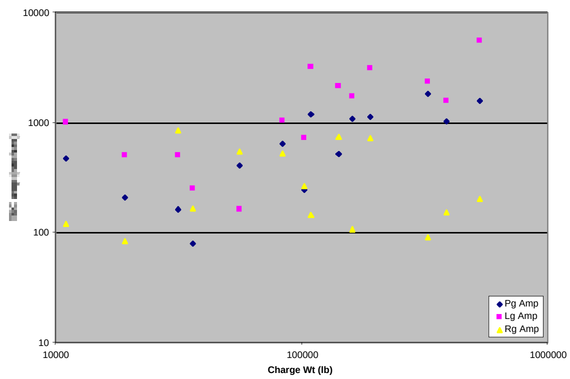

Figure 11: Peak amplitudes of the regional phases P_g, L_g and R_g measured at the regional station TUC (Figure 1) for the events listed in Table 1.

CONCLUSIONS AND RECOMMENDATIONS

The development of an integrated data set of ground truthed explosions that include multiple seismic and infrasonic observations across a regional network is underway. Critical to this study is the development of the ground truth information which has motivated the installation of seismic and acoustic instruments in two hard rock copper mines. Preliminary analysis of this data indicates that the blasting practices from such mines are quite different from coal cast blasting (Pearson *et al.*, 1995) including the near-simultaneous detonation of multiple explosive patterns and shots with no delays. Since these explosions are primarily designed to fracture rock, there is little casting or horizontal movement of the material. Figure 12 includes four frames from a video of a hard rock mining explosions and captures the relatively short time duration and the minimal post shot displacement.

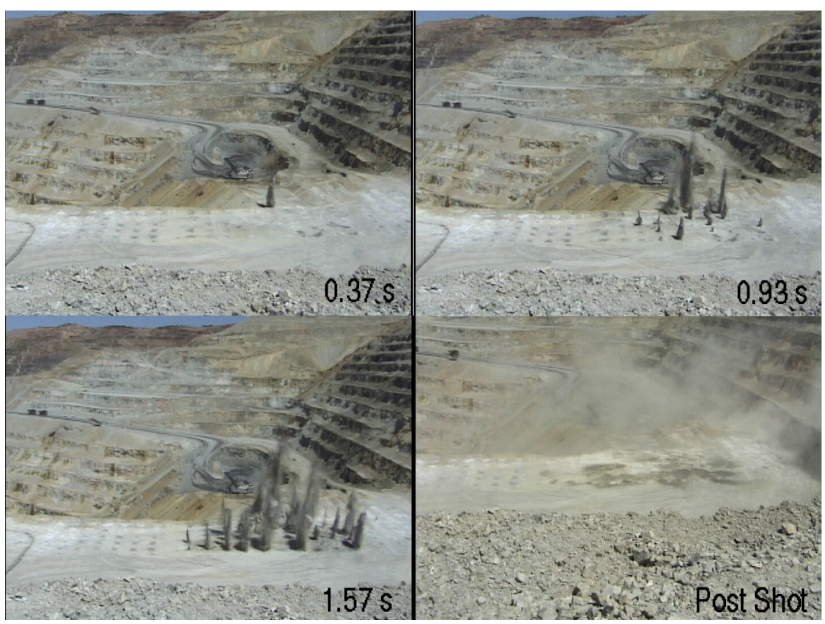

Figure 12: Four video frames from a hard rock mining explosion designed to fragment the material. The relative source time is designated in the lower right of each image.

The completion of the regional network is anticipated in the summer of 2000 providing the opportunity to extend the data base further. The network will remain in place in order to document the effects of seasonal variations in the atmosphere on the infrasound signals generated by these mines. This data set is intended to support a modeling effort to quantify infrasonic wave propagation effects as well as investigate source information that may be retained in these regional signals.

Preliminary analysis of the combined in-mine and regional data sets illustrates the utility of such studies in quantifying source and propagation path effects. The in-mine acoustic data suggests a strong source contribution that must be compared to the regional data. This data is also useful in identifying complex blasting practices that may include the detonation of multiple explosive patterns over time periods of a second or less. The implication of such a blasting practice on regional seismic and infrasonic signals will be explored. The time separation between patterns could be responsible for low frequency spectral scalloping that has been observed by other researchers.

Portable seismic and infrasonic stations will be deployed to quantify the effects of range on the infrasonic signals filling in between the semi-permanent stations diagramed in Figure 1. This data along with atmospheric models in the region will provide the basis for extension of an infrasonic modeling effort.

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